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RESEARCH ARTICLE

Short Converging Pneumatic Conveyor Used for Conveying of Solids Modelling, Analysis, and Simulation of Manufacturing Processes

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ABSTRACT

Pneumatic conveying is defined as the transport of particulate solids by a gaseous stream through any flow channel. This operation has been used in process industries for a long time, just for transport of several kinds of particulate solids, such as lime, coal, polymer pellets, soda ash and granular chemicals etc. The different types of material chosen for the experiment are sago (Cycas revoluta), red lentil (Lens culinaris), black mustard (Sinapis nigra) and white mustard (Sinapis alba). The present work, deals with the experimental work of a slightly modified vertical pneumatic conveying system where the conveying line is converging from 0.0762 m to 0.0508 m. The modeling of the above setup is also carried out so as to compare the data received by theoretical and experimental calculations.

Key words: Pneumatic conveying, Sample preparation, Experimental set up, Modelling of pneumatic Conveying system.

1. INTRODUCTION

Pneumatic conveying has long been a popular choice for moving bulk materials, either from storage facilities to a process unit, or between process units. Generally speaking, mechanical systems make sense with short, straight runs within a plant; they require less horsepower and sometimes can be less expensive in terms of capital cost but they are usually a higher-maintenance choice, have problems with dust generation or contamination of process material, and are not as flexible in dealing with plant-floor configurations [1],[2]. Given sufficient capital, there is nothing that cannot be pneumatically conveyed. Pneumatic systems run cleaner than mechanical ones and are less susceptible to product contamination. So recycling of materials is easier in this system [3].

Pneumatic Conveying has decisive advantages over mechanical conveying in conveying dusty products like low space requirements and low maintenance [4],[5]. Also it is flexible in construction, can be easily automated, provides dustless conveying without loss of material and is thus also safe for products hazardous to health [6]. A conveyable product is transported through a pipe by using a certain quality of gas (air or nitrogen)[6],[7]. The product particles are freely moving with a high gas velocity and a low product to air ratio. Pneumatic conveying is a clean and efficient way for food processors to transport raw ingredients from point A to point B in a completely contained manner [8]. Pneumatic conveyors use compressed air to either push or pull material through a fully enclosed horizontal or vertical conveying line [9]. The conveying pipe or tube can be constructed from a variety of materials, the most frequently used one being stainless steel for food operations, and can vary in diameter. The wider the diameter of the conveying line, higher is the conveying rate. [10].

Any pneumatic conveying system shall have four basic components namely prime mover which develops motive force (roots blower, compressor or centrifugal fan), feeding

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device which introduces product into diverters and product to air separator (cyclone, bag filter). Typically the systems are bifurcated into two main categories - Pressure type & Vacuum type. They are sub categorized into dense phase and dilute phase conveying [10].

2. MATERIALS AND METHODS

2.1. Sampling

The different type of materials chosen for the experiment are sago (Cycas revoluta), red lentil (Lens culinaris), black mustard (Sinapis nigra) and white mustard (Sinapis alba). The size range and average diameter of various samples used are given in table A1 and density of the various samples used is calculated and are shown in table 1. [11]

Table 1.Density of the various samples used

Material	Density(Kg/m3)
Small Sago [11]	1240
Large Sago [11]	1170
Red Lentil [11]	1504
Black Mustard [11]	1027.5
White Mustard [11]	1570

2.2. Equipment and experimental set-up

2.2.1. Short convergingv pneumatic conveying system

The existing experimental set up figure B1 consists of a transport tube having a length of 2.7 and diameter conveying from 0.0762m to 0.0508 m with all other accessories for gas and solid feeding and solid separation cyclone.

2.2.2. Various parts of the experimental set up

The short converging vertical riser consists of the following parts

1. Vertical converging transport tube.
2. (Cyclone separator.
3. Vertical leg of cyclone separator.
4. Solid feeding tube.
5. Solid storage bin.
6. Air blower.
7. Common connector for pressure taps.
8. Two water manometers.
9. Orifice plate.

2.2.3. Vertical converging transport tube

The converging transport tube or the riser is made up of acrylic sheets hot-rolled in A_l pattern. The vertical riser consists of 24 pressure taps made of brass tubes, which are connected to the common connector by polythene tubes. The bottom of the transport tube is fitted with a valve (V_4) for by passing a part of blower air in order to control the airflow rate through the transport tube. This valve is also used to discharge the solid from the system at the end of each experimental run. The top of the transport tube is connected with the cyclone separator. Axial length of this tube is 270mm. Distance between two successive taps is 11cm. Tube diameters at the bottom (d_1) =0.0762 m and at the top (d_2) = 0.0508m.

2.2.4. Cyclone separator

It is also fabricated by means of acrylic tubes and sheets. The separator is so designed that it can separate all the solid particles from the outgoing air stream from the transport tube or riser. The separator is connected with the bottom vertical leg to download the separated solids out of the cyclone by gravity.
Dimensions: diameter of upper cylindrical portion=16.72cm, height of this upper cylindrical portion=33cm, height of lower conical portion=33cm, height of next lower vertical leg=186cm, length of bottom most leg=30cm.

2.2.5. Vertical leg of cyclone separator

The bottom leg of the separator is made of a 5.08 cm acrylic tube fitted with a valve (V_1) in order to control the solid discharge, which is recycled to the solid feeding tube again. The valve is also used to measure the solid circulation rate which is achieved by closing the valve. Height of this vertical leg=186 cm. Diameter of this lower vertical leg=4.18 cm.

2.2.6. Solid feeding tube

The solid feeding tube is made of 2.05cm brass tube and grounded to the earth in order to discharge the electrostatic charges of the re-circulated solids. The inclined feeding tube is connected to the bottom of the transport tube to feed the solid into the upward flowing

air through the transport tube. The tube is also connected with a solid storage bin to feed the fresh solid at the start of the experiment.

2.2.7. Solid Storage Bin

The storage bin is made of mild -steel sheet and fitted with acrylic slit to observe the level of the solids at any instant. It also helps to find the solid feeding rate as and when required. The bottom of the bin is connectedthrough the valve (V_2) to the solid feeding tube in order to control the solid feeding rate.

2.2.8. Air blower

An air blower is connected to the bottom of the transport tube for sending air through the vertical transport tube. The blower is fitted with orifice meter to measure the airflow rate.

2.2.9. Common connector for pressure taps

Common pressure tap-connector drum is made of acrylic tube and sheets. All the pressure taps of the vertical transport tube are connected to the common connector through the brass valves. A single tube from the centre of the common connector is connected with one end of a water manometer. By opening the individual valves of the pressure taps the differential pressure reading may be measured by connecting the other end of the manometer with the bottom most pressure tap of the transport tube.

2.1.10. Three water manometer

There are three water manometers used in this experiment. One is used to measure the differential pressure readings along the vertical transport tube. Another is used to adjust the compressed air flow through the solid feeding in order to restrict the air leakage from the transport tube and another one is used to measure the gage pressure of the air sent through the bottom of the vertical transport tube.

2.2.11. Orifice meter

The airflow rate from the blower is measured by means of orifice meter and is done by measuring pressure difference within it.

2.3. Experimental procedure

- All the physical parameters of the solid particles have been estimated earlier.
- The storage bin is first loaded with desired particulate solids.
- Air is sent from the blower.
- Solid is charged slowly by opening the valve (V_2) fitted at the bottom of the storage bin so that particles can be fluidized continuously without retaining those particles at the bottom of the converging tube. After completing the charging V_2 is closed.
- For easy feeding of the solid & to eliminate the leakage of air through the solid feeding line compressed air is sent through the tube fitted co-axially with the solid feeding line.
- This airflow is adjusted so as to restrict the air leakage from the transport tube towards the solid feeding line.
- The solid particles is observed to be transported by the air flowing through the vertical converging transport tube & separated from the air stream by the cyclone separator fitted at top of the vertical transport tube.
- The solid feeding rate is verified by closing intermittently valve (V_1) fitted with the leg of the cyclone separator.
- Differential pressure is measured across the various pressure taps and the base pressure taps (bottom most) of the transport tube.
- The data thus collected for various differential pressures at different heights of the transport tube were plotted against the height of the transport tube with different solid particles at constant airflow rate & compared with the theoretical differential pressure profiles.

3. MODELLING AND PNEUMATIC CONVEYING SYSTEM

3.1. Assumptions

The assumptions are as follows

- The particles are uniformly distributed throughout the cross section of the vertical conduit immediately after introduction through the feed point. The radial uniformity of particle concentration is maintained all through the height.
- Radial variations in gas and particle velocities are assumed to be absent. There exist only axial velocity gradients during the transport of particles along the accelerating zone.
- From the instant of release into the upward flowing air, the solid particles experience three types of forces. Firstly the upward

fluid drag exerted by air, secondly the gravitational force due to the weight of solids and finally the solid frictional force because of the surrounding tube wall. The last two forces are acting as retarding forces on the particles in the downward direction. It is presumed that no other forces like lift, magnetic or electrical force are acting on the particles.

- Particles are spherical in shape.
- The physical and transport properties of the fluid medium (air) such as temperature, and viscosity as well as the density remain substantially constant which is justified by using an average value [Averaging is done between inlet and outlet conditions] of these properties.
- The aforesaid assumptions do not alter in case of converging transport tube since the angle of convergence of the tube in the present experimental set-up is very small (0.53o)
- The frictional force of the particle is estimated by the [12] ratio relationship as given below

$$F_S = \frac{2f_s u_P^2}{d_t} \quad (3.1)$$

The above equation (3.1) is valid for unit mass.Total mass of the solid in elemental height. The details of equations are (3.2), (3.3), (3.4), (3.5), (3.6), (3.7), (3.8), (3.9), (3.10), (3.11), (3.12), (3.13), (3.14), (3.15), (3.16), (3.17), (3.18), (3.19), (3.20) and (3.21) as shown below.

dh= (total volume of the solid in elemental height, dh) × (density of the particle)

$$m = \left(\frac{\pi d_t^2}{4}\right) dh(1-\varepsilon)\rho_p \quad (3.2)$$

$$F_s = \frac{2f_s u_P^2}{d_t}\left(\frac{\pi d_t^2}{4}\right) dh(1-\varepsilon)\rho_P \quad (3.3)$$

$$f_s = \left(\frac{3}{8}\right)\left(\frac{\rho_g C_d d_t}{d_P \rho_P}\right)\left(\frac{u_g-u_P}{u_P}\right)^2 \quad (3.4)$$

Therefore,

$$F_s = \frac{2u_P^2}{d_t}\left(\frac{3}{8}\right)\left(\frac{\rho_g C_d d_t}{d_P \rho_P}\right)\left(\frac{u_g-u_P}{u_P}\right)^2\left(\frac{\pi d_t^2}{4}\right) dh(1-\varepsilon)\rho_P \quad (3.5)$$

$$= \frac{0.75\rho_g C_d}{d_P \rho_P}\left(\frac{u_g-u_P}{u_P}\right)^2\left(\frac{\pi d_t^2}{4}\right) dh(1-\varepsilon)\rho_P$$

$$F_s = \frac{0.75\rho_g C_d}{d_P}\left(\frac{u_g-u_P}{u_P}\right)^2\left(\frac{\pi d_t^2}{4}\right) dh(1-\varepsilon)\rho_P \quad (3.6)$$

Here, d_t = tube diameter at any arbitrary height, h is assumed from the bottom point of the converging tube (which varies along with the height of the converging tube vertically) and is modified in the present case.

$$d_t = \frac{[(H-h)d_1 + h \times d_2]}{H} \quad (3.7)$$

where,

H = axial length of the converging tube (or, vertical height);

d_1 = bottom most diameter of the tube;

d_2 = top most diameter of the tube;

h = any arbitrary height considered from the bottom most point of the converging tube.

The drag co-efficient, C_d attains constant value of 0.44 in the Newtonian regime and is equal to 24/Rep in the laminar region. A generalized expression for C_d has been suggested by [13] follows:

$$C_d = \left(\frac{k_1}{Re_P}\right) + \left(\frac{k_2}{Re_P^2}\right) + k_3 \quad (3.8)$$

where, $Re_P = \frac{(u_g-u_P)d_P\rho_g}{\mu_g}$ and k_1, k_2, k_3 are empirical constants which assumes different values for different ranges of Re_p.

The buoyant force due to the fluid medium is negligible in comparison with the gravitational force acting on the particle.

Void fraction is calculated using the formulae

$$\varepsilon = \frac{\{{}^{m_g}/{}_{l_g}\}}{\{{}^{m_P}/{}_{l_P}\} + \{{}^{m_g}/{}_{l_g}\}} \quad (3.9)$$

Viscosity of gas is calculated using the formula

$$\mu_g = \frac{m_g}{l_g \times \frac{\pi}{4} \times d_f^2} \quad (3.10)$$

Pressure drop due to acceleration of gas is calculated using the formula,

$$d_{Pag} = 0.5 \times l_g \times \varepsilon \times u_g^2 \quad (3.11)$$

Calculation of the terminal settling velocity is done by the following formula

$$u_f = \left[\frac{4}{3} \times \frac{(l_s - l_g)}{l_g} \times \frac{g \times d_P}{c_d}\right]^{0.5} \quad (3.12)$$

Reynolds number of particle is calculated using the formulae,

$$Re_P = \frac{u_f \times d_P \times l_g}{\mu_g} \quad (3.13)$$

The value of Rep is send to a data base and a new value of drag coefficient is calculated, depending on the range and the value of Rep is in the range as reported by the previous research group [13].

$$C_d = \frac{k_1}{Re_P} + \frac{k_2}{Re_P^2} + k_3 \quad (3.14)$$

Pressure drop due to solid particles is calculated using the formulae,

$$d_{Pas} = l_P \times (1-\epsilon) \times u_P^2 \quad (3.15)$$

Friction factor of solid is calculated using the formulae,

$$f_s = \left(\frac{3}{8}\right)\left(\frac{l_g C_d d_f}{d_P l_s}\right)\left(\frac{u_g - u_P}{u_P}\right)^2 \quad (3.16)$$

Pressure drop due to friction between solid and tube wall is calculated, using the formulae,

$$d_{pfs} = \frac{2 \times f_s \times l_p \times (1-\varepsilon) \times u_P^2 \times h_o}{d_f} \quad (3.17)$$

Pressure drop due to friction between gas and tube wall is calculated using the formula,

$$d_{pfg} = \frac{2 \times f_g \times l_g \times (\varepsilon) \times u_g^2 \times dh_o}{d_t} \quad (3.18)$$

Pressure drop due to static head of gas is calculated using the formula,

$$d_{pss} = l_g \times \varepsilon \times g \times dh_o \quad (3.19)$$

Pressure drop due to static head of solid is calculated using the formula

$$d_{pss} = l_g \times (1-\varepsilon) \times g \times dh_o \quad (3.20)$$

The total pressure drop occurring in the converging tube at the required height is

$$d_{Pf} = d_{Psg} + d_{Pfg} + d_{Pss} + d_{Pfs} + d_{Pas} + d_{Pag} \quad (3.21)$$

4. RESULTS AND DISCUSSION

4.1. Theoretical simulation

The theoretical results are shown after calculation using the Turbo C++ 3.0.The details are shown in below figures B2, figures B3, figures B4, figures B5, figures B6 and figures B7.

4.1.1. Small sago

Conditions:

Velocity of inlet air = 2.17m/sec
Diameter of particle = 1.6
Temperature = 30°C
Density of small sago = 1240 kg/m^3
Density of air = 1.1872 kg/m^3
Air flow rate = 0.02933 kg/sec

4.1.2. Large sago

Conditions:-

Velocity of inlet air = 2.24m/sec
Diameter of particle = 3.75mm
Temperature = 34°C
Density of large sago = 1170kg/m^3
Density of air = 1.1684 kg/m^3
Air flow rate = 0.0338 kg/sec

4.1.3. White mustard

Conditions:-

Velocity of inlet air = 2.17m/sec
Diameter of particle = 1.85mm
Temperature = 30°C
Density of white mustard = 1570kg/m^3
Density of air = 1.1872 kg/m^3
Air flow rate = 0.03242 kg/sec

4.1.4. Black mustard

Conditions:-

Velocity of inlet air = 2.07m/sec
Diameter of particle = 1.905mm
Temperature = 32°C
Density of black mustard = 1027 kg/m^3
Density of air = 1.1772 kg/m^3
Air flow rate = 0.03116 kg/sec

4.1.5 Red lentil

Conditions:-

Velocity of inlet air = 2.13m/sec
Diameter of particle = 2.75mm
Temperature = 32°C
Density of red lentil = 1347 kg/m^3
Density of air = 1.1772 kg/m^3
Air flow rate = 0.0322 kg/sec

4.2. Theoretical Values

Large Sago, Small Sago, Black Mustard, White Mustard, Red Lentil and Air

5. DISCUSSIONS

The experimental pressure drop data collected from pressure taps at different heights of the riser using different particulate solids are given in the table 1.

Case 1: Comparative study of pressure drop profile for two different circulation rates

It is observed that with higher solid circulation rate the exponential trend is more. It can also by confirmed that the total pressure drop is high for high solid circulation rate at any height of the riser.

Case 2: Comparative study of pressure drop profile for converging and uniform tube

These theoretical plots are derived from the model by using computer program. In these figures the profiles show that the pressure drop of converging tube is gradually increasing at a faster rate than that of the uniform tube. The gradient of pressure drop profile is gradually increasing with the riser height which does not happen in case of uniform tube. This is because of the fact that the particulate solids in case of converging tube is under constant acceleration and are transported subsequently with increasing velocity and is never attaining the steady state velocity.

6. CONCLUSIONS

An initial prediction of the particulate mode of flow in pneumatic conveying systems is beneficial as this knowledge can provide clear direction to the pneumatic conveying design process. There are three general categories of modes of flow, out of which two are dense flows viz fluidized dense phase and plug flow, and the other category is dilute phase. This paper presents a review of the commonly used and available techniques for predicting mode of flow.

Two types of predictive charts were defined:

- Basic particle parameter based (e.g. particle size and density) and
- Air-particle parameter based (e.g. permeability and de-aeration).

The basic particle techniques were found to have strong and weak areas of predictive ability, on the basis of a comparison with data from materials with known mode of flow capability. It was found that there was only slight improvement in predictive ability when the particle density was replaced by loose-poured bulk density in the basic parameter techniques. To a certain extent, all the previous diagrams have shown that they have good predictive capabilities for one or more particular pneumatic conveying 'modes of flow'. The basic particle diagrams generally give an accurate prediction of fluidized dense phase capabilities and to a lesser extent, the plug flow capable materials when 'loose-poured' bulk density is applied. However, a significant number of plug-type and dilute only endowed materials are clustered together in a transition zone which shows that for basic bulk material-based charts there is a region where it is difficult to separate materials into different modes of flow.

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APPENDIX A

Table A1.Size range and average diameter of various samples used

Material	**Size Range (ISS screen) u**	**Average Diameter**
Small Sago	- 1.72mm +1.50mm	1.61mm
Large Sago	- 4mm +3.5mm	3.75mm
Red Lentil	- 3mm +2.5mm	2.75mm
Black Mustard	- 2mm +1.81mm	1.905mm
White Mustard	- 2mm +1.70mm	1.85mm

APPENDIX B

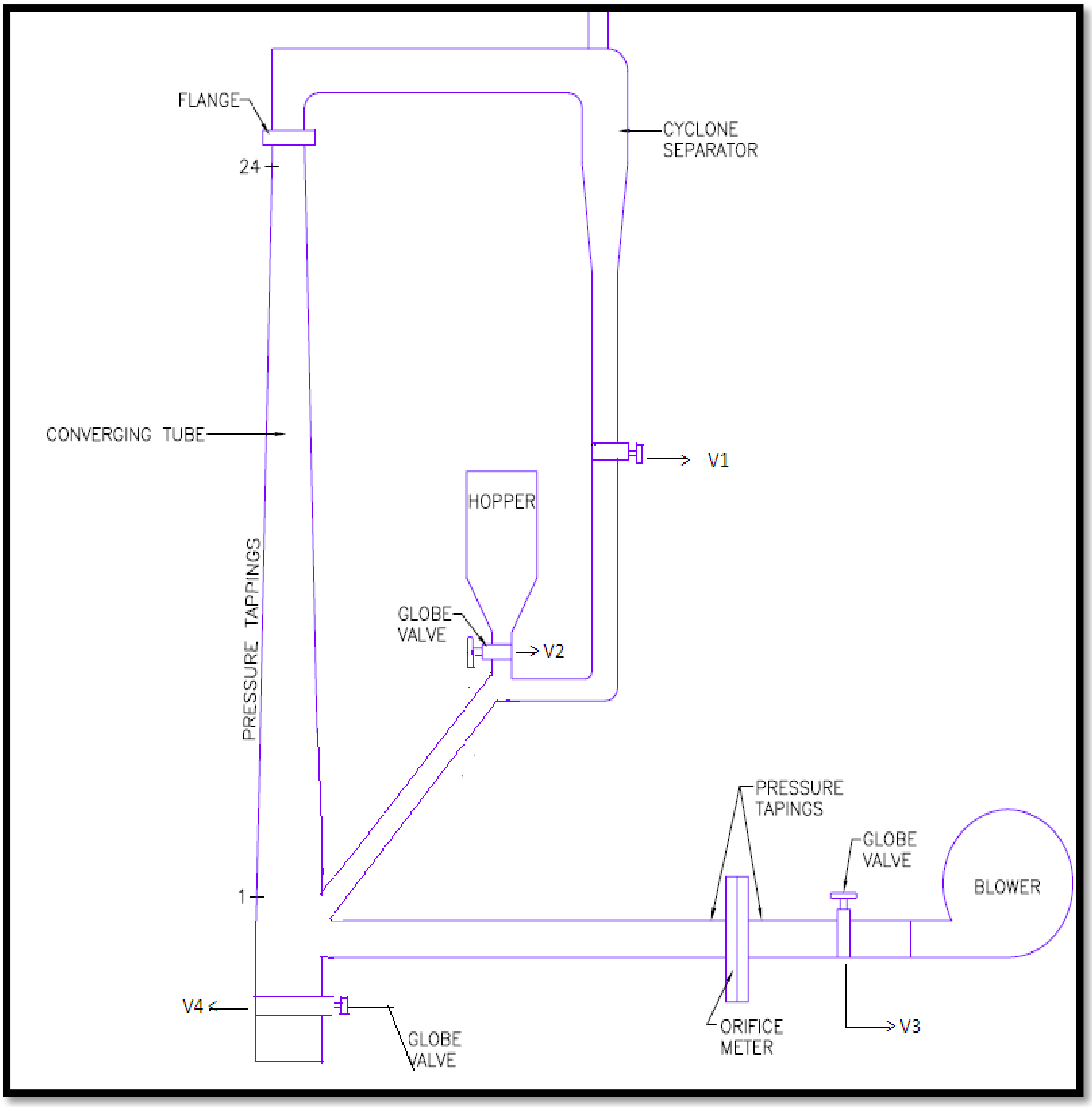

Figure B1.Short converging vertical pneumatic

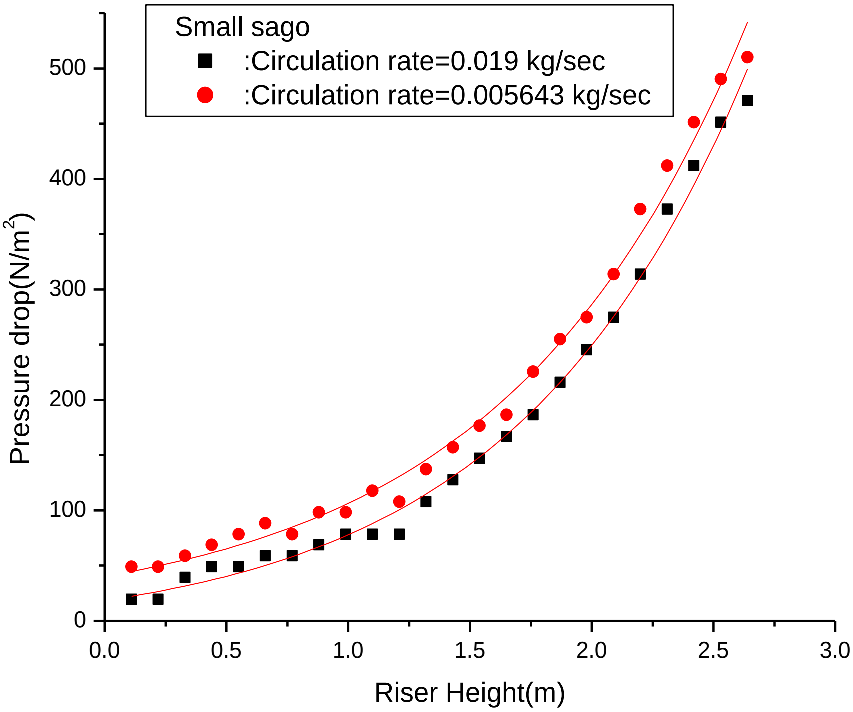

Figure B2.Pressure drop against the riser height for small sago

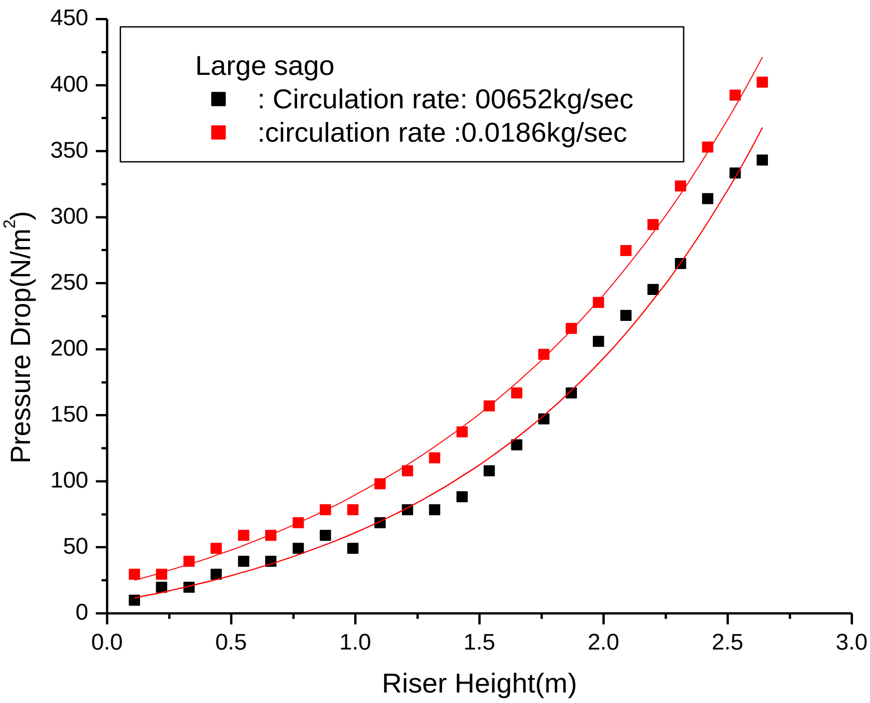

Figure B3.Pressure drop against the riser height for large sago

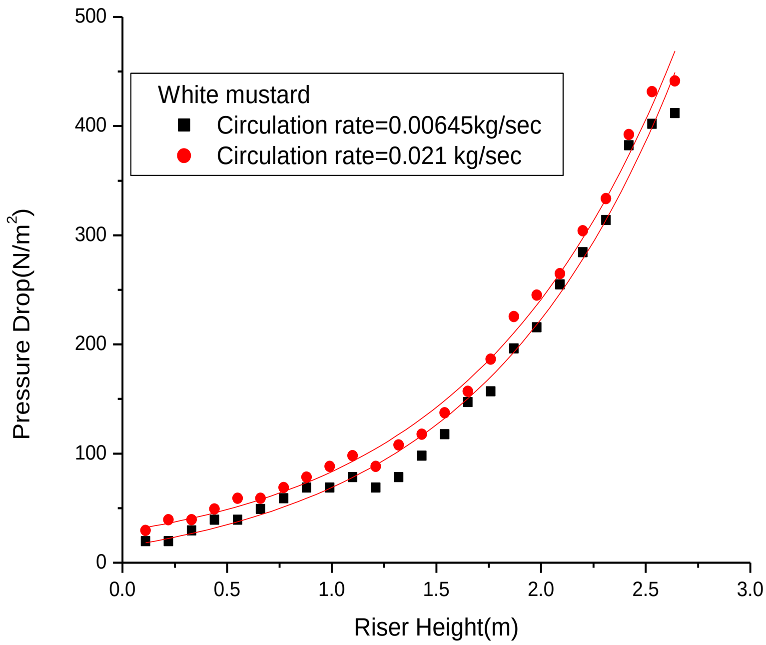

Figure B4.Pressure drop against the riser height for white mustard

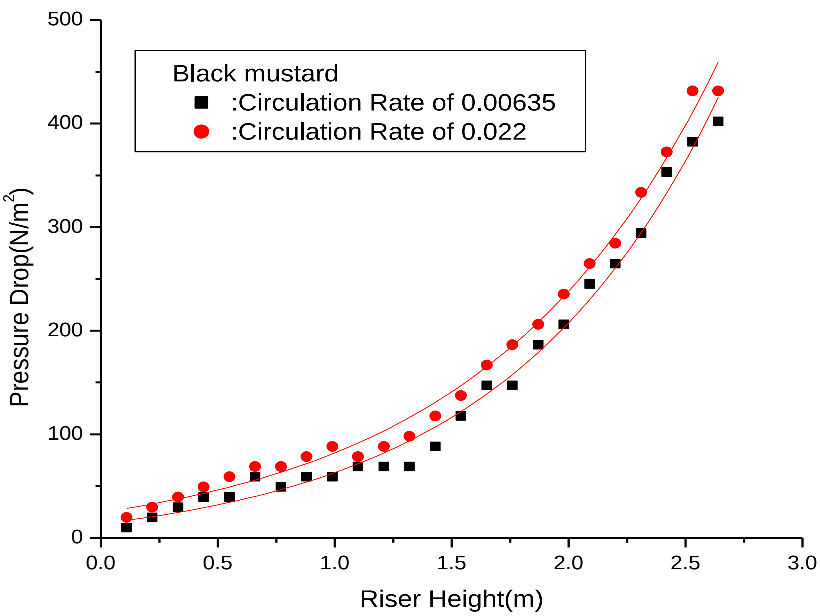

Figure B5.Pressure drop against the riser height for black mustard

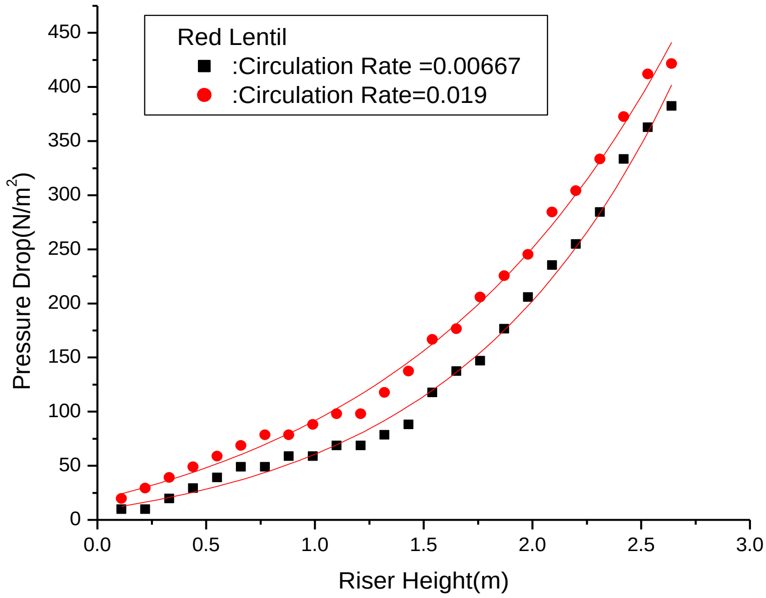

Figure B6. Pressure drop against the riser height for red lentil

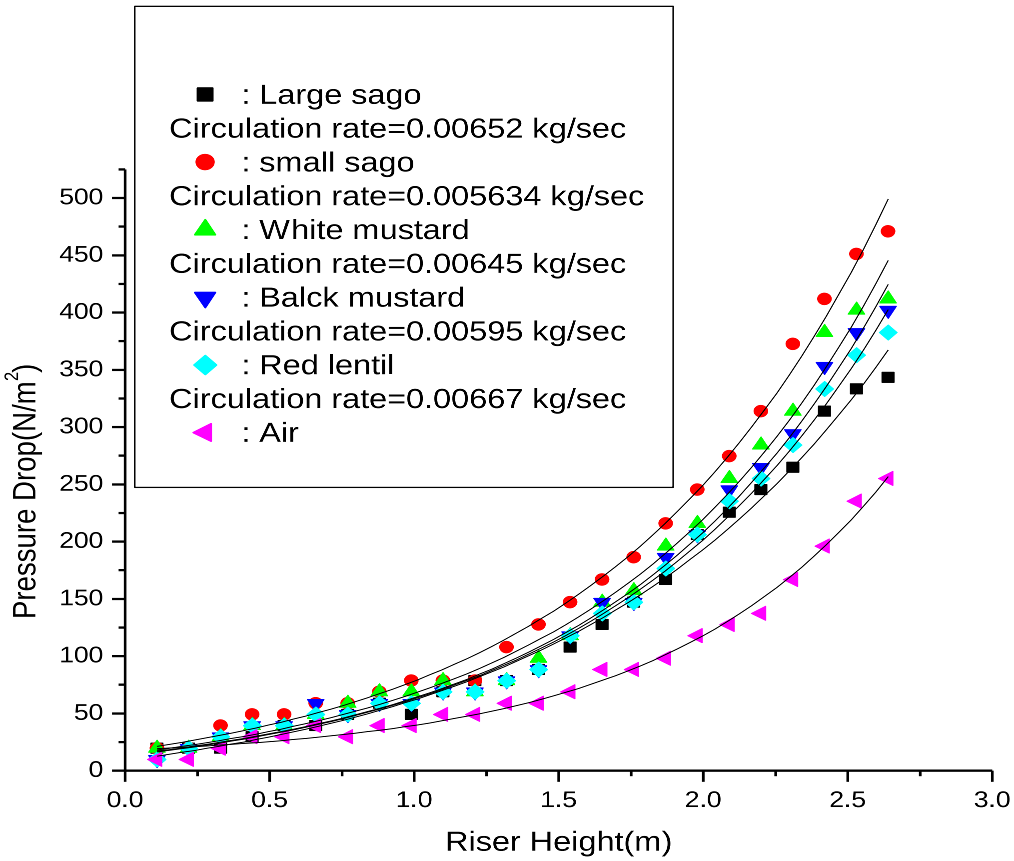

Figure B7.Theoretical pressure drop against riser height amongst all the samples